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A study into the vibration behaviour of power ultrasonic devices for bone surgery

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Abstract

Nonlinear behaviour is known to exist in power ultrasonic systems. Multimodal responses, frequency modulations, hysteresis effects, bifurcations and chaos are amongst the nonlinear phenomena detected in tuned devices driven at high power.

This paper investigates the effect of a cutting insert on the inherent nonlinear vibration behaviour of an ultrasonic transducer for bone surgery. The mode shape and operating mode of the tuned assembly have been simulated using finite element analysis (FEA) and validated by experimental modal analysis (EMA). The effects of temperature and power on the system nonlinear response characteristics have also been measured using a laser vibrometer (LDV) and a thermal imaging camera. Hints for the design of power ultrasonic devices with controlled vibration behaviour ensue from the work.

Keywords: Ultrasonic surgical devices; Nonlinearities; Frequency shift; EMA

1. Introduction

High power ultrasonics applies to industrial technologies ranging from chemical and food processing to drilling and welding operations, as well as to medical procedures including HIFU and bone surgery [1, 2]. The micrometric vibrations exploited in ultrasonic systems are commonly generated by piezoceramics (PZT) which constitute the active part of ultrasonic transducers. Despite power ultrasonics hold many advantages over conventional technologies, the inherently nonlinear behaviour of tuned systems, largely descending by PZT electromechanical properties, hinders the development of further applications [3, 4]. Combination resonances, frequency shifts, jump-resonance hysteresis, modulations, bifurcations and chaos, are typical nonlinear phenomena which affect the stability of power ultrasonic systems [5].

In this paper the characterization of the vibration behaviour of an ultrasonic device for bone surgery, particularly its nonlinear response at high power, is reported. In order to better understand the device vibration characteristics, tests have been conducted removing thermal contributions to the nonlinear velocity responses. Hence, a relationship between nonlinear responses, drive conditions and system configurations has been sought. The understanding of the

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nonlinear dynamics of tuned systems stemming from this work, aims to progress design strategies for most power ultrasonic devices.

2. Ultrasonic bone cutting

A novel power ultrasonic device for hard tissue dissection has been recently developed by Mectron S.p.A [6]. Such an instrument, known as the Piezosurgery® Device, constitutes a major improvement over conventional bone cutting instruments which are commonly responsible for tissue burning, imprecise dissections and debris formation. The consequences of these undesirable effects can result in slow bone healing. This device has been designed to operate on various surgical sites without damaging nearby tissue. Clinical trials have proven that the vibrations piezoelectrically engendered in this tuned instrument allow precise and safe cutting even on highly mineralised bones. Piezosurgery is currently adopted in a growing range of maxillofacial operations such as orthognatic surgeries, implantology, lower arch ridge expansions [2,7].

2.1. Finite element model

The Mectron instrument consists in a piezoelectric ultrasonic transducer powered by an ultrasonic generator, which operates in conjunction with a number of cutting inserts designed for various surgical uses. A model of a cutting insert (OT7) mechanically coupled with the ultrasonic transducer is shown in Figure 1(a). Figure 1(b) illustrates the nominal deflection mode of this assembly predicted using a commercial FEA code (ABAQUS). The flexural vibrations achieved at the insert cutting edge are exploited to dissect bone.

To understand the means through which the vibration movements of the cutting insert can be achieved, this tuned assembly has to be divided into two subsystems. The first subsystem consists of the transducer and the base of the insert, whereas the second one is formed by the insert shank and cutting edge (Figure 1(a)). The transducer/base subsystem has been tuned to the first longitudinal mode at a frequency near 28 kHz. The second subsystem has been designed to facilitate its insertion in the surgical area, and to exhibit a flexural mode at a frequency close to the longitudinal frequency. Hence, the full system has been predicted to operate in a longitudinal-flexural composite mode at 27.9 kHz.

2.2. Experimental modal analysis

The Figure 1(c) shows the mode shape of the composite vibration mode of the device extracted using EMA. EMA was performed exciting the system with a random excitation over a 0-50 kHz frequency range, and collecting modal responses on a grid of points on the structure using a 3D LDV (Polytec, CLV-3D). Then, measured frequency response functions were curve-fitted using LMS modal software. Hence, assembly modal parameters could be extracted. An excellent correlation between the predicted and experimentally extracted tuned frequency and mode shape was achieved, as revealed by inspection of Figures 1(b) and 1(c).

3. Measurements of nonlinear responses

Ultrasonic transducers operate exploiting the inverse piezoelectric effect of the PZT elements. When an AC voltage is passed across a PZT stack this deforms generating stress waves. At low stress, responses and properties of PZT are linear. However, in power ultrasonic applications, tuned devices are driven into a mode at high excitation voltages which cause high dynamic stress and consequent nonlinear behaviours. It is well-known that PZT nonlinear vibration behaviour is influenced by two conditions; high stress, caused by elevated amplitudes, and temperature increases, due to the losses in PZT [4]. When an ultrasonic system is driven using a continuous excitation PZT temperature increases over time until generated and radiated heat reach equilibrium. To test the vibration characteristics of tuned devices, without having to wait for thermal equilibrium conditions to be reached, temperature effects on PZT characteristics need to be removed.

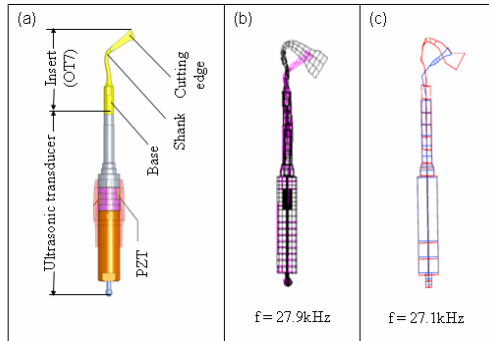


Fig.1 (a) Model of the Mectron device; (b) Modal data of the system obtained with FE, (c) EMA

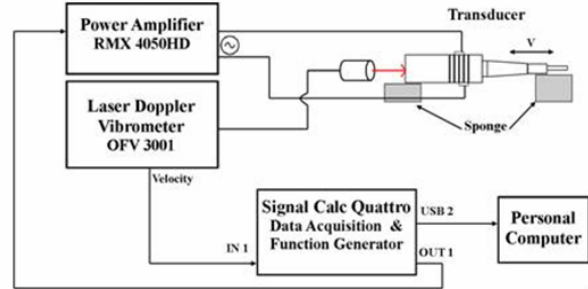


Fig.2 Schematic Diagram of Experimental Setup

3.1. Removal of temperature effect on response

A method to appraise the level of nonlinearity of an ultrasonic system consists in the measurement of its response characteristic near the tuned frequency. To this end, upward and downward sweeps of the excitation frequency are commonly performed at increasing power levels. Shifts of the tuned frequency and hysteresis-like effects in the measured frequency response curves are typical signs of the nonlinear behaviour exhibited by power ultrasonic devices [3-5].

During sweep response tests when the driving frequency is set at the resonance value, PZT temperature increases at the highest rate and maximal variations of the piezoelectric properties occur. To separate thermal contributions to the response characteristics of tuned resonators, Umeda *et al.* have shown that non-continuous (or burst) excitations can be adopted [4]. By this method, the ultrasonic apparatus is excited at each frequency of the driving range for a short period of time. The period is long enough to allow response detections and processing while short enough to greatly reduce heating of PZT. In this work non-continuous sinusoidal signals, equal to one-second-long AC voltages, were used to excite the investigated systems. Despite temperature increases which still occurred at high vibration amplitude thermal effects were eliminated by allowing the device time to cool between successive frequency increments.

3.1.1. Experimental setup for response measurements

Figure 2 shows a schematic of the experimental setup utilized to perform frequency-response measurements of the Mectron device. During sweeping tests the device was driven using a signal generator and analyser (Data Physics, Quattro), and a power amplifier (QSC Audio, RMX 4050HD). The device vibration velocities were measured with a 1D LDV (Polytec, OFV 3001), as illustrated in the figure. Data Physics, SignalCalc 240 was the software employed to perform FFT on the responses.

3.1.2. Thermal measurements

A thermal imaging camera (Thermoteknix Miricle 110k) was used to identify thermal distributions in the tuned devices, during testing. Temperature measurements were used to estimate the time intervals to be awaited between successive increments of the driving frequency so that the responses could be collected at the same (room) temperature. A thermal image of the ultrasonic device was acquired at room temperature, under no excitation, and used as reference. Such an image was then subtracted from the images captured in rapid succession on the device after removal of the one-second excitation. Once one of the successive images cancelled with the reference image leaving a blank frame, it could be assumed that initial temperature conditions had been reached; thus the waiting time could be estimated. At high power levels, and near the device resonance frequency, waiting times reached the order

of several minutes. Figure 3 shows a thermal image of a transducer/insert OT7 assembly, captured right after excitation removal. As expected, the hottest spot arose in the PZT.

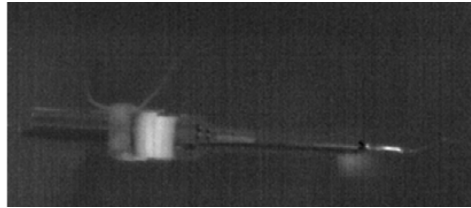


Fig.3 Thermal image of the transducer with OT7 insert

3.1.3. Temperature effect on vibration responses

Figure 4, shows two frequency-response plots attained for the transducer/insert OT7 assembly driven in the 26.8–27.4 kHz range. Figure 4(a) shows the velocity responses detected when sweeps of the driving frequency were carried out using a continuous signal. Responses obtained under a non-continuous excitation, are shown in Figure 4(b). In this case, cooling time was allowed between successive frequency increments, during testing.

At 5 V drive, both plots exhibited symmetric responses, implying that at low power the assembly operated within its linear regime, independently of the excitation type. At 100 V excitations, nonlinear response characteristics appeared, and, decreases of the tuned frequencies from the linear value occurred. In particular, under non-continuous drive, a frequency shift of 120 Hz took place (Figure 4(b)). Conversely, a shift of 240 Hz resulted when continuous excitation conditions were adopted (Figure 4(a)). The frequency-response plots detected at 100 V mainly differentiated in the vibration velocities obtained during downward frequency sweeps. This was because, under continuous drive, heat generated in PZT, especially after the upward jump, during the frequency sweep up, affected the electromechanical properties. As a result, responses measured during the frequency sweep down were influenced by the change of PZT properties.

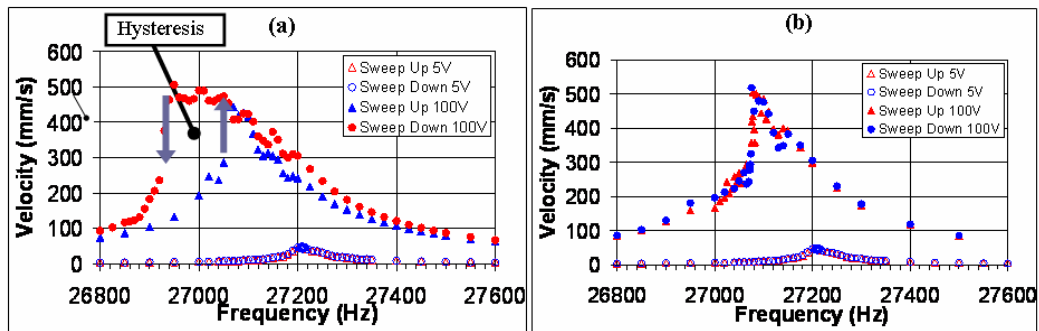


Fig.4 Mectron transducer connected to insert OT7. Velocity responses versus frequency under (a) continuous excitation, (b) one-second long bursts and allowing cooling time

Figure 4(a) reveals a wide hysteretic zone bordered by upward and downward jumps of the velocity responses. Again, the occurrence of hysteresis was largely due to the temperature increase effects. The performance of systems operating within hysteresis loops is typically unsteady, and their driving is problematic. Hence, to avoid nonlinear effects due to thermal variations, non-continuous excitations need to be adopted for the characterization of the vibration behaviour of tuned devices.

4. Results

Previous research from this group has shown that horns operated in conjunction with power transducers are themselves source of nonlinearities which can affect the overall response characteristic of tuned assemblies [5]. A study of the change of response characteristics with power is therefore crucial to find design strategies for robust driving circuits of ultrasonic systems. In this work, three configurations of the Mectron device were selected to identify mutual effects between the power transducer and attached units.

4.1. Transducer/insert OT7 assembly

Figure 5 illustrates the frequency response curves obtained for the tuned longitudinal-flexural mode of the transducer/OT7 assembly. Forward and backward sweeps of the driving frequency were conducted at four power levels, using the non-constant excitation method. To thoroughly portrait the system response characteristics, smaller increments of the driving frequency were adopted in proximity of resonance, wherein response variation were more abrupt. At high power levels, the measured response curves revealed a prominent softening characteristic. Jump phenomena and formation of hysteresis loops, typical of nonlinear systems, were also identified at higher voltages.

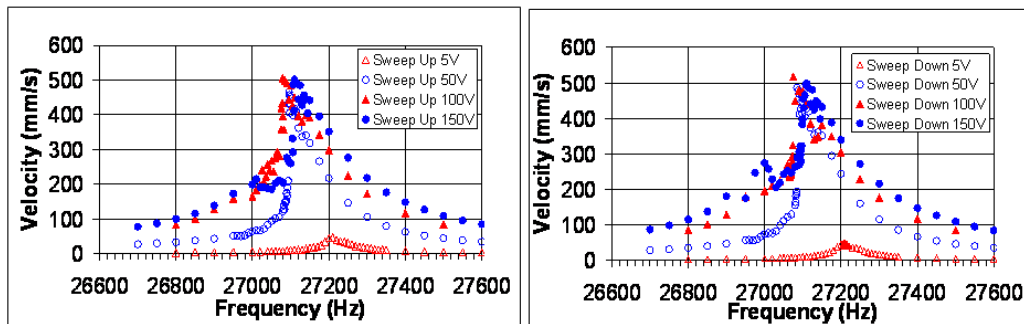


Fig.5 Mectron transducer connected to insert OT7. Velocity versus frequency at increasing drive voltages

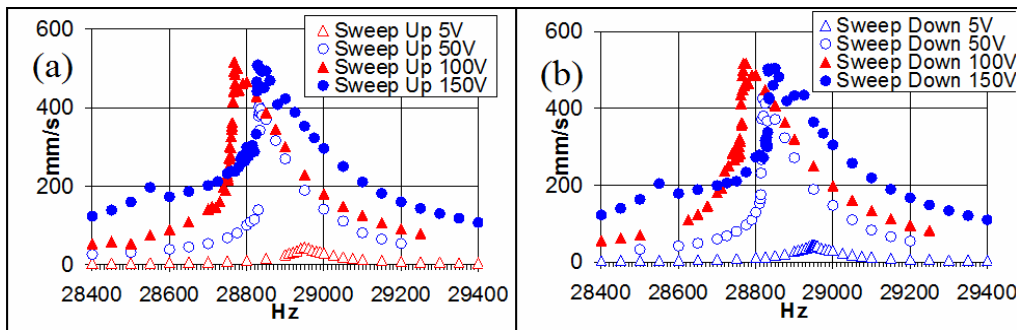


Fig.6 Mectron transducer connected to insert base. Velocity responses versus frequency at increasing drive voltages

4.2. Transducer/insert base assembly

The cutting inserts used in the Piezosurgery® Device all have an identical base, whilst differentiate in the stem and cutting edge profiles. Hence, response tests of the transducer attached to an insert base were conducted around

the assembly longitudinal frequency (Figure 6). As for the transducer/OT7 configuration, frequency responses bent toward the lower frequency side forming hysterical regions, as the driving voltage increased.

4.3. Transducer without insert

To assess whether the attached cutting inserts had an effect on the response characteristics of the Mectron device, a final set of frequency response tests were carried out on the transducer alone. In this case, the longitudinal frequency of the transducer resided in the 36 kHz region (Figure 7). Again the device tuned frequency measured at 50, 100 and 150 V resulted lower than that measured at 5 V, confirming the device nonlinear behaviour.

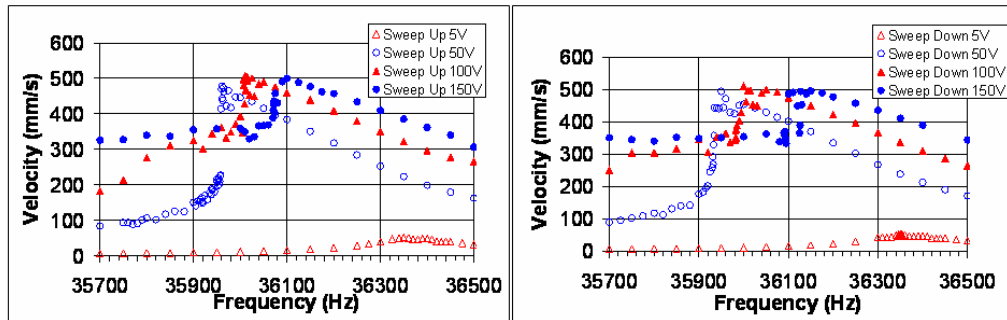


Fig.7 Mectron transducer without insert. Velocity responses versus frequency at increasing drive voltages

5. Discussion

Frequency response measurements conducted on the Mectron device revealed that, at higher powers, the tuned frequency decreases with respect to its low power value. These findings are in line with previous studies on piezoelectric ultrasonic resonators, in which the elastic constant of PZT has been found responsible for tuned frequency reductions [4].

Nevertheless, in the present work it was noticed that the decrease of the resonant frequency from the linear value (at 5 V) reduced when excitation voltages exceeded certain thresholds. Figures 8 plots the trends of the frequency decreases versus driving voltages obtained for the tested system configurations. The trend of the frequency decrease of an assembly consisting in the transducer/insert base system with a support flange sandwiched between PZT, is also plotted.

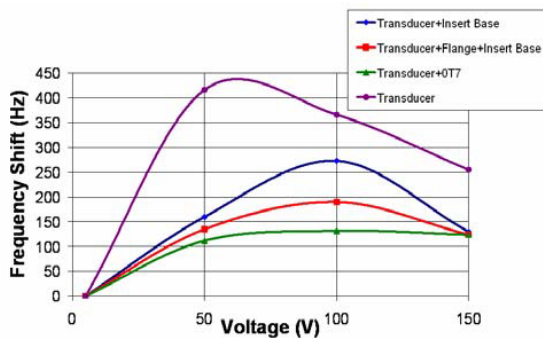


Fig.8 Variations of the tuned frequency vs driving voltage

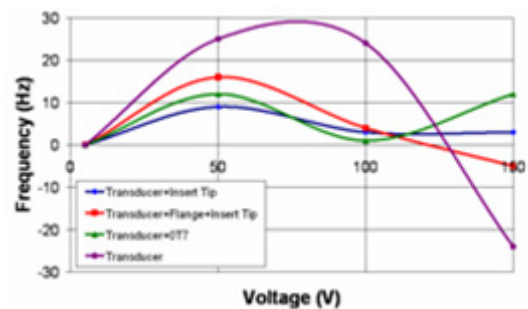


Fig.9 Frequency width of the hysteresis vs voltage

It can be observed that when driving voltages were increased from 100 V to 150 V, or above 50 V, for the transducer alone case, tuned frequency decreases consistently reduced. It appears that above these power thresholds, some other type of nonlinearity mitigated the PZT nonlinear response characteristic. At this moment, it is not clear how these mitigating effects were generated; in particular, whether their origin was only mechanical or electrical too. It is however thought that in the transducer, hardening effects could stem from the threaded interfaces between the prestressing bolt and end masses, and that the flange could also have an effect. Similarly, the threaded connection between the transducer and the cutting insert could be a source of nonlinearity. The flexural mode excited in the stem/cutting edge subassembly might also be inherently nonlinear.

Figure 9 shows the frequency width of the hysteresis region given by the difference between response jump up and drop down frequencies, versus driving voltage. When a tuned system happens to be driven within a hysteresis loop, it might respond at two amplitudes depending on the initial conditions. To avoid this instability, it is beneficial that resonators are not driven within these loops. Also from figure 9, it can be noticed that at 100 V, the frequency width of the unstable zone is minimal for all configurations investigated, but the transducer alone. This implies that this voltage constitutes an optimal driving condition for the tuned assemblies. This holds, despite at 100 V occurred the largest decrease of the resonant frequency. For the transducer alone case, optimal driving is expected at around 125 V. Even so, the transducer was designed to operate attached to an insert.

6. Conclusions

In this work the vibration characteristics of an ultrasonic bone cutting device were presented. A study of its vibration behaviour under different driving conditions and power levels was experimentally characterized. Specifically it was found that the nonlinear behaviour of the investigated assemblies varied with the driving voltages. In particular, it was noticed that various type of nonlinearities influenced the response characteristic of ultrasonic devices. Finally, optimal driving conditions, for a device stable performance were identified. Further studies will be aimed to identify and manipulate nonlinearities of opposite effects, not only to improve frequency stabilities, but also to enhance response amplitudes of power ultrasonic systems.

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